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Feeding of western gray whales during a seismic survey near Sakhalin Island, Russia

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Abstract Exxon Neftegas Limited, as operator of the Sakhalin-1 consortium, is developing oil and gas reserves on the continental shelf off northeast Sakhalin Island, Russia. DalMorNefteGeofizika (DMNG) on behalf of the Sakhalin-1 consortium conducted a 3-D seismic survey of the Odoptu license area during 17 August–9 September 2001. A portion of the primary feeding area of the endangered western gray whale (*Eschrichtius robustus*) is located in the vicinity of the seismic survey. This paper presents data to assess whether western gray whale bottom feeding activity, as indicated by visible mud plumes, was affected by seismic operations. The mitigation and monitoring program associated with the seismic survey included aerial surveys during 19 July–19 November 2001. These aerial surveys documented the local and regional distribution, abundance, and bottom feeding activity of western gray whales. Data on gray whale feeding activity before, during and after the seismic survey were collected, with the whales assumed to be feeding on the benthos if mud plumes were observed on the surface. The data were used to assess the influence of seismic survey and other factors (including environmental) on feeding activity of western gray whales. A stepwise multiple regression analysis failed to find a statistically significant effect (α=0.05) of the seismic survey on frequency of occurrence of mud plumes of western gray whales used as a proxy to evaluate bottom feeding activity in Piltun feeding area. The regression indicated that transect number (a proxy for water depth, related to distance from shore) and swell height (a proxy for sea state) were the only variables that had a significant effect on frequency of whale mud plumes. It is concluded that the 2001 seismic survey had no measurable effect (α=0.05) on bottom feeding activity of western gray whales off Sakhalin Island.

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Introduction

The Western North Pacific population of gray whale (*Eschrichtius robustus*), hereinafter western gray whale, feeds off northeastern Sakhalin Island, Russia. A primary feeding area (Piltun feeding area) lies parallel to shore from 52°37.5′ N to 53°37.5′ N in a narrow strip (ca. 100×5 km) mainly within the 20-m isobath along the coast of northeast Sakhalin Island and adjacent to Piltun Bay. Western gray whales are one of the most endangered populations of large cetaceans. The International Union for the Conservation of Nature (IUCN) listed the western gray whale as critically endangered, based on its geographic and genetic separation from the eastern population (LeDuc et al. 2002) and because of the likelihood that fewer than 50 reproductively active individuals remain in the population (Hilton-Taylor 2000). This population is also listed as Category 1 (“threatened by extinction”) in the Red Book of the Russian Federation (Anonymous 2001).

Exxon Neftegas Limited, as operator of the Sakhalin-1 consortium, is developing oil and gas reserves on the nearshore continental shelf off northeast Sakhalin Island, Russia. DalMorNefteGeofizika (DMNG) on behalf of the Sakhalin-1 consortium conducted a 3-D seismic survey of the Odoptu license area during 17 August–9 September 2001. The data presented here were collected to evaluate whether the feeding activity of western gray whales was affected during this seismic survey. Feeding activity index is defined as the proportion of gray whale groups observed with mud plumes relative to the total number of gray whale groups recorded in the Piltun survey grid. To reduce and assess potential impacts of the seismic survey on western gray whales, mitigation and monitoring programs were designed and implemented (Johnson 2002; Johnson et al. 2007). One component of the monitoring program included replicated and systematic aerial surveys. The aerial surveys determined the local and regional distribution, abundance and bottom feeding-related activity of western gray whales. The distribution and abundance of gray whales in relation to the 2001 Odoptu 3-D seismic survey are addressed elsewhere (Yazvenko et al. 2007).

This paper presents the results of observations of gray whale bottom feeding-related activity before, during and after the seismic survey in 2001. The goal of this study was to determine whether the feeding activity index changed in relation to the seismic survey. Specifically, the objectives were (1) to determine if bottom feeding activity of gray whales was affected by the seismic survey in the Odoptu Block area and assess the influence of various environmental factors and seismic-survey related parameters on this activity, and (2) to characterize the spatial and temporal variability of feeding activity of gray whales within the study area. “Feeding” is used throughout the paper to indicate the activity resulting in visible mud plumes. No inference is made related to the quantity and quality of food intake resulting from this activity.

Materials and methods

Aerial survey area

The Piltun aerial survey grid developed for the 3-D seismic survey covered coastal areas, (two transects in waters <20 m deep; two transect lines (hereinafter “lines”) outside the 20 m isobath), near and seaward of Piltun Bay and adjacent to the Odoptu seismic block, i.e., areas where gray whales have been found to aggregate to feed (Blokhin et al. 1985, 2002, 2003, 2004; Berzin et al. 1988, 1990, 1991; Blokhin 1996; Sobolevsky 2000, 2001; Weller et al. 2000, 2001; Yazvenko et al. 2002; Vladimirov et al. 2005; Meier et al. 2007). Four ~90-km long lines were established parallel to the shore, spaced 2 km apart covering from 52° 43′ N to 53° 31′ N; each line was subdivided into five “blocks” numbered sequentially from south to north (Fig. 1). This sampling grid included all areas where western gray whales were known to feed in the Piltun feeding area prior to 2001.

Survey design

After several attempts failed due to weather, the first successful aerial survey was flown on 19 July. Surveys were usually conducted daily or several times per day, weather permitting, until 19 November, more

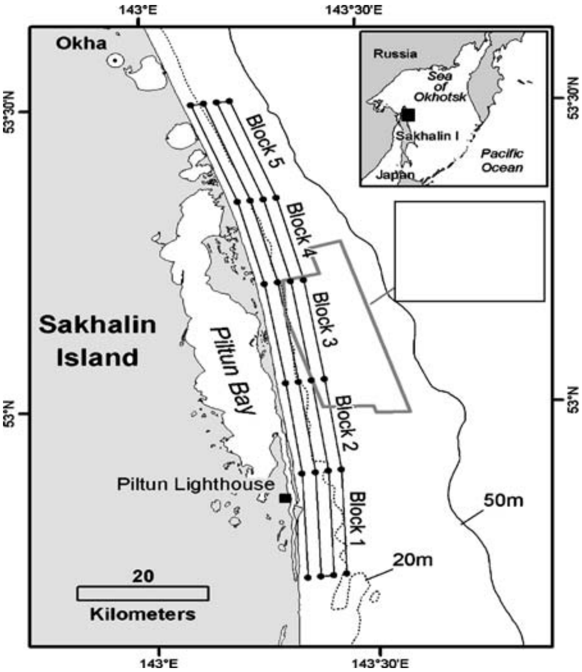

Fig. 1 Piltun aerial survey grid developed for the 3-D seismic survey monitoring with four 90-km-long transects parallel to coast and numbered seawards. Each of the four transects was subdivided into five "blocks"

than 2 months after seismic operations ceased (see Table 1).

The seismic survey ceased at 3:45 A.M. on 9 September 2001. All surveys conducted on or after 9 September occurred after the cessation of the seismic survey. All but one survey were flown at 300 m above sea level (ASL); the survey on 7 October was flown at various altitudes due to rapid changes in weather conditions. Survey procedures generally followed those recommended by the High Energy Seismic Survey (HESS 1999) team guidelines for southern California waters. Aerial surveys were an important part of the mitigation and monitoring program and used in daily planning (Johnson 2002; Johnson et al. 2007). Other components of the program included a vessel-based marine mammal monitoring program (Meier et al. 2002), acoustic monitoring of noise levels on the periphery of the area frequented by gray whales (Borisov et al. 2002; Rutenko et al. 2007), and a shore-based gray whale behaviour monitoring program (Würsig et al. 2002; Gailey et al. 2007).

Prior to 4 August, aerial surveys were conducted in a twin-engine MI-8 helicopter. Surveys were flown with three marine mammal observers, one on each side of the aircraft behind the pilots and one in the front nose-pod of the cockpit (i.e., forward of and between the pilot and co-pilot). Beginning on 4 August, an Antonov 28 (AN-28) twin engine turboprop fixed-wing aircraft was used. Two side observers and a data recorder conducted surveys. Both aircraft were equipped with a radar altimeter. In addition to the aircraft GPS, marine mammal observers had a dedicated Garmin© III+ GPS that every 30 s automatically logged track-line positions of the survey route (see Yazvenko et al. 2002 and Blokhin et al. 2002 for details).

Survey procedures

A whale sighting was defined as an observation of a group, i.e., of one or more western gray whales and/or one or more mud plumes that are usually visible when gray whales feed on benthic organisms and expel bottom sediment at or near the surface. A gray whale or a group of whales was considered associated with mud plume(s) if the distance between a whale and the closest plume was less than five body lengths apart. Otherwise, a mud plume was considered not associated with whales and eliminated from the analysis (14.8% sightings). Whales were considered a group

Table 1 Periods of the 2001 field season and frequency of aerial surveys

Period	Seismic activities	Aerial surveys	Mud plumes recorded
19 Jul morning–2 Aug morning	No seismic survey	One to two surveys a day, weather permitting	Yes
Afternoon 2 Aug–16 Aug	Seismic calibration	One to four surveys a day, weather permitting	Yes
17 Aug–8 Sept	Seismic survey	One to three surveys a day, weather permitting	Yes
9 Sept–27 Oct	No seismic survey	One to three surveys a day, weather permitting	Yes
28 Oct–14 Nov	No seismic survey	No surveys	N/A
15–19 Nov	No seismic survey	One to two surveys a day, weather permitting	Yes

using the same criterion (less than five body lengths between whales). GPS coordinates were recorded as way-points at the point of closest approach to a gray whale/plume sighted during the survey, i.e., when the whale and/or plume was directly perpendicular to the aircraft. Clinometers were used to measure the vertical angle to gray whale individuals and groups, as well as to mud plumes. These angles were used to determine the distance of the sighting from the aircraft. Location information for seismic support vessels and small craft was recorded in the same manner as for whales and mud plumes.

During an average 4.1 min surface-respiration-dive cycle recorded in 2001 in the Piltun feeding area ("surface time" plus "dive time" in Würsig et al. 2002), gray whales spent approximately 1.6±1.84 min on the surface ("surface time") and 2.5±0.92 min underwater ("dive time"). Thus, gray whales were on the surface for about 40% of the time in the Piltun feeding area, though the variability of "surface time" was high. At ground speeds of ~180 km/h for the MI-8 and ~200 km/h for the AN-28, the availability of gray whales (Buckland et al. 1993) averaged 0.446 for both aircraft and all sightability conditions (J. Muir, LGL Limited, unpublished data).

Data analysis

The geographic areas defined by each of the five blocks×four line combinations (Fig. 1) were viewed as the main experimental units upon which whale sightings, environmental variables, and seismic survey variables were measured. Only 3.5% of gray whales were sighted on lines 3 (covering the strip 4–6 km offshore) and 4 (covering the strip 6–8 km offshore), the two lines farthest offshore, which lie for the most part outside the 20-m isobath (Yazvenko et al. 2002). Therefore, 96.5% of the sighted gray whales were located within 4 km of shore. Because a high proportion of zeros (surveys without whale sightings) on lines 3 and 4 would adversely influence the stability of the analyses, lines 3 and 4 were excluded from the analyses. Similarly, only 1% of whales were sighted on all lines in block 5, the northernmost of the five surveyed blocks (Fig. 1); therefore, data from this block were omitted from the analyses.

The response variable for this analysis was the proportion of feeding groups of whales observed during each survey of each of the eight blocks (geographic areas). Whale groups engaged in feeding behavior were defined to be those observed in close proximity to a feeding plume. If a group of whales was associated with a feeding plume, it was assumed that all members of the group were feeding. The response of the logistic regression analysis can be written,

$$\text{Feeding Index} = \pi_i = {}^{f_i}\!/_{w_i},$$

where f_i was the number of groups of whales observed on survey i definitely associated with a feeding plume, and w_i was the number of groups of whales on survey i that were associated with a feeding plume (i.e., f_i) plus the number of groups of whales definitely not associated with a feeding plume. A survey was defined as one flight over one of the geographic areas.

Overall, data for 728 groups of 740 gray whales were used. Whale sightings that occurred while the aircraft was turning or travelling to another transect were excluded from regression analyses. Only the gray whale sightings that were definitely associated with mud plume(s) or were definitely not associated with mud plume(s) were included in these analyses (69% of sightings). During surveys, the sightability of whales and mud plumes decreased with distance from the transect (Fig. 2; Yazvenko et al. 2002). To limit this effect, only groups and plumes sighted within 400 m of either side of the aircraft were included in the analyses. No distance analysis (Buckland et al. 1993) was performed, because it was the ratio of whale groups with plumes *vs* total whale groups, rather than density of whale groups, that was the object of the study. This ratio was not likely to be affected by slight changes in sightability with distance from the aircraft. Plus, the "object" being detected was different in numerator and denominator. In numerator, "plumes+whales" were detected while in denominator, it was "whales." Application of correction methods would be complicated; therefore, only those data where the detection was high were considered.

Multiple regression analysis of gray whale bottom-feeding activity

Stepwise multiple regression (Neter et al. 1983) was used to consider (1) environmental variables that could influence feeding activity and (2) seismic sound variables associated with the seismic survey that could

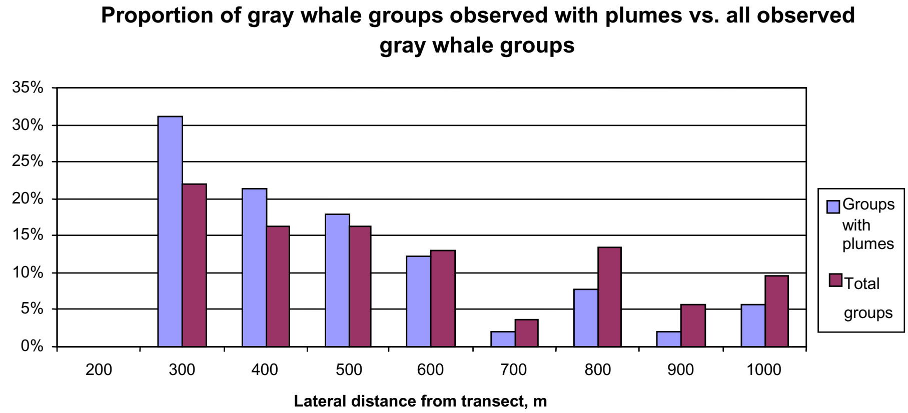

Fig. 2 Proportion of gray whale groups presumed bottom-feeding (gray whales definitely associated with mud feeding plumes) *vs* proportion of all gray whales sighted at different distance intervals from the transect. Only sightings on lines 1 and 2 in the Piltun survey area were considered. Sightings within the blind strip beneath the aircraft (<200 m of the transect centerline at survey altitude of 300 m) are not included

influence whale feeding activity. The regression model was fitted to the observed data. If estimated seismic sound energy levels explained a significant fraction of the residual variation in the proportion of whale groups observed with mud plumes not explained by environmental variables, we reasoned that seismic survey noise had influenced the proportion of whale groups that were observed with mud plumes.

The response variable for this analysis was the feeding activity index (π) obtained during each survey of each of the eight geographic areas. The logistic model used here was similar to a regular regression model in that it related a function of the proportion of whale groups with mud plumes to a linear function of study variables (Eq. 1):

$$\begin{aligned}\text{logit}(E[\pi_i]) &= \ln\left[\frac{E[\pi_i]}{1-E[\pi_i]}\right] \\ &= \beta_0 + \beta_1 X_{1i} + \ldots + \beta_p X_{pi}\end{aligned} \tag{1}$$

where β_j were unknown coefficients, and X_{ji} were values of the jth explanatory variable measured during the ith survey. The variance of π_i was modelled as (Eq. 2):

$$var\,(\pi_i) = \phi[w_i \pi_i (1-\pi_i)] \tag{2}$$

where ϕ was an unknown *over-dispersion* parameter to be estimated. The over-dispersion parameter ϕ was estimated as the sum of squared Pearson residuals divided by residual degrees of freedom. Wald χ^2 statistics (=estimate^2/estimate's variance) were computed to indicate the significance of variables in the final model and to test differences between one level and its reference.

Stepwise multiple regression with forward variable selection was used to create a logistic model containing significant environmental variables. During each forward step of this procedure, environmental and other non-seismic variables in consideration (Table 2) were added one-at-a-time and the χ^2 score statistics testing the hypothesis of no contribution to the overall fit was computed. Score statistics were adjusted for variables already in the model. The most significant variable was then added to the model. Following each forward step, an iterative reassessment was conducted of the significance of variables in the current model. The statistical significance of terms now in the model was assessed using χ^2 score tests and the variable with the greatest p value was removed (provided that the p value was greater than α=0.05). This process continued until no variables significantly contributed to the model during a forward step, and no variable was eliminated through iteration.

During model selection, linear terms for main effects (e.g., *date* and *hour*) were required in the model before quadratic terms were allowed. As a result, only linear effects that were not previously in the model, and quadratic effects of variables already in the model, were available for addition during the forward steps.

To avoid model instability caused by large numbers of missing values, *b_speed, c_speed, u_speed, b_dir, c_dir, u_dir* were excluded from consideration.

Table 2 The list of environmental and other non-seismic related variables considered for inclusion in the logistic regression model for the gray whale feeding activity analysis

Variable	Description
line	Transect line number (1 or 2)
block	Block number (1 to 4)
visibility	Visibility index (0, 0.5, 1, 1.5, 2, 2.5, 3, 3.5, 4, 4.5, 5)
white_caps	Incidence of white-caps (0, 0.5, 1, 1.5, 2)
fog	Index of fog (0, 1, 2)
wind_direction	Direction of wind (N, E, S, W)
wind_speed	Wind speed (m/s)
air_temp	Air temperature (°C)
wave_height	Wind wave height (m)
swell_height	Swell height (m)
swell_period	Swell period (s)
level	Estimated tide (m)
storm3	Hours since storm with wave height >3 m
storm4	Hours since storm with wave height >4 m
date	Julian date (number of days since January 1, 1960)
time	Hours since midnight
sea state	Sea state index (0, 0.5, 1, 1.5, 2, 2.5)
overcast	Percent overcast (%)
aircraft	MI-8 (helicopter) or AN-28 (fixed-wing)
*aircraft*fog*	Interaction between aircraft and fog
*aircraft*visibility*	Interaction between aircraft and visibility
*aircraft*white_caps*	Interaction between aircraft and white_caps
*aircraft*overcast*	Interaction between aircraft and overcast
wave_period[b]	Wind wave period (s)
sun[b]	Index of sun (0, 0.5, 1)
depth[b]	Depth (m)
b_speed[a]	Bottom current speed (mm/s)
b_direction[a]	Bottom current direction (N, E, S, W)
u_speed[a]	Surface current speed (mm/s)
u_direction[a]	Surface current direction (N, E, S, W)
c_speed[a]	All-depths average current speed (mm/s)
c_direction[a]	All-depths average current direction (N, E, S, W)
B2T1[a]	Shoreward distance (m) from block center to T1 position
seg3h	Sound energy estimate for preceding 3 h period
seg3d	Sound energy estimate for preceding 3 day period
rubin3h[a]	Position of Rubin relative to block center position in preceding 3 h period
rubin3d[a]	Position of Rubin relative to block center position in preceding 3 day period
atlas3h[a]	Position of Atlas relative to block center position in preceding 3 h period
atlas3d[a]	Position of Rubin relative to block center position in preceding 3 day period

[a] Variables removed from analysis due to large number of missing observations or insufficient data.

[b] Variables removed from analysis due to high collinearity with another variable.

Multiple collinearity (Neter et al. 1983) existed between *line* and *depth* (Pearson correlation coefficient r=0.88) and between *sun* and *overcast* (r=−0.824); therefore, *depth* and *sun* were dropped from consideration. Because *wave_height* was included in the model and served as a reliable measure of sea state, *sea state* was subsequently removed. The variable *B2T1*, shoreward distance from the center of the block to the point where sound energy estimates were calculated, was unique to every block and thereby was confounded with the *block* variable. *B2T1* was dropped from consideration because *block* was easier to interpret. To avoid fitting too many parameters in the model, interactions between any of the categorical variables – *aircraft*, *visibility, white_caps, fog*, and *overcast* – were not considered in this analysis. One of the important variables that would be beneficial to the logistic regression analysis, *prey availability*, was not considered because of the lack of site-specific data.

Certain variables listed in Table 2 represented industrial effects and were not considered for inclusion in model as environmental variables. Some of these industrial variables relied on definition of a 'T1' point. The T1 point for each of the 20 geographic areas in the study area (Fig. 1) was the geographic center of the area, except in cases where the geographic center was in water less than 20 m deep. In those cases, the T1 point was moved perpendicularly offshore to the closest point on the 20-m isobath (Yazvenko et al. 2002). Autonomous sonobuoys with bottom-mounted hydrophones were used to measure received sound levels in the study area in the frequency band 10–5000 Hz and to transmit them to a shore station where the signals were monitored in real time. Sonobuoys were deployed along the 20-m isobath, at the offshore edge of the Piltun feeding area (Rutenko et al. 2007). The shift of the T1 point farther offshore towards the seismic source was a conservative step to allow for a more specific and accurate determination of estimated seismic energy reaching the block. This determination was based on case-by-case modelling of propagation from the offset T1 point to the geographic center of the geographic area.

Seismic survey-related variables of interest included estimates of total sound energy, *seg*, at T1 during the 3-h (*seg3h*) and 3-day (*seg3d*) period preceding an aerial survey (Yazvenko et al. 2002). An estimate of sound energy from the seismic survey for specific locations and time periods was computed based on the gun volume of the shots during that period. These estimates were computed by (1) computation of sound energy per shot at 1 m from the source, (2) computation of sound attenuation through the water column using a simple spreading model, specifically $25 \times \log_{10}(\text{distance})$, (3) computation of received energy for each seismic shot by applying the spreading model to the distance between the sound source and T1 locations, and (4) summation of the resulting estimates of received energy per shot at T1 locations over the time period of interest.

Sound energy 1 m from the source during both the calibration and seismic survey was estimated for 100 in^3 (55% of the shots), 370 in^3 (2.5%), 1,640 in^3 (40%) and 3,090 in^3 (2.5%) air gun volumes (Borisov et al. 2002; Rutenko et al. 2007). Sound energy 1 m from source was estimated for the remaining air gun volumes by interpolation. Average energy received at T1 locations per shot for all shots in a given period was estimated by dividing the sum of the individual shot energies (from the previous steps) by the number of shots fired during the relevant period.

Following stepwise selection of a model containing environmental variables, *seg3h* and *seg3d* were added separately to the model containing significant environmental variables. The "best" of the three models was determined by inspection of individual Wald *t* tests for *seg3h* and *seg3d* and choosing the one with the smallest p value ($\alpha \leq 0.05$). If both seismic variables had p values greater than $\alpha=0.05$, i.e., their effects on the model were statistically insignificant at $\alpha=0.05$, and the model containing only environmental variables was chosen as the "best" of the three models. Significance of any seismic sound term would indicate a seismic survey effect if a statistically significant portion of the variation of whale feeding activity could be explained by sound energy variables that could not otherwise be explained by environmental conditions.

To check that temporal autocorrelation in the proportion of whales with mud plumes was not adversely affecting significance levels of terms in the final logistic model, deviance residuals from the final model were assessed for temporal correlation using Moran's I statistic (Moran 1950). The Moran's I varies between −1.0 and +1.0. If the points that are close together in time have similar values, the Moran's I value is high. If temporal correlation was found in the residuals, generalized mixed linear model estimation procedures were used to specifically allow for temporal correlation. However, generalized mixed linear models were difficult to construct and were avoided when possible.

Results

To more closely examine trends in feeding activity during the study period, the mud-plume dive data were partitioned into time periods that corresponded to the different seismic survey regimes (Fig. 3).

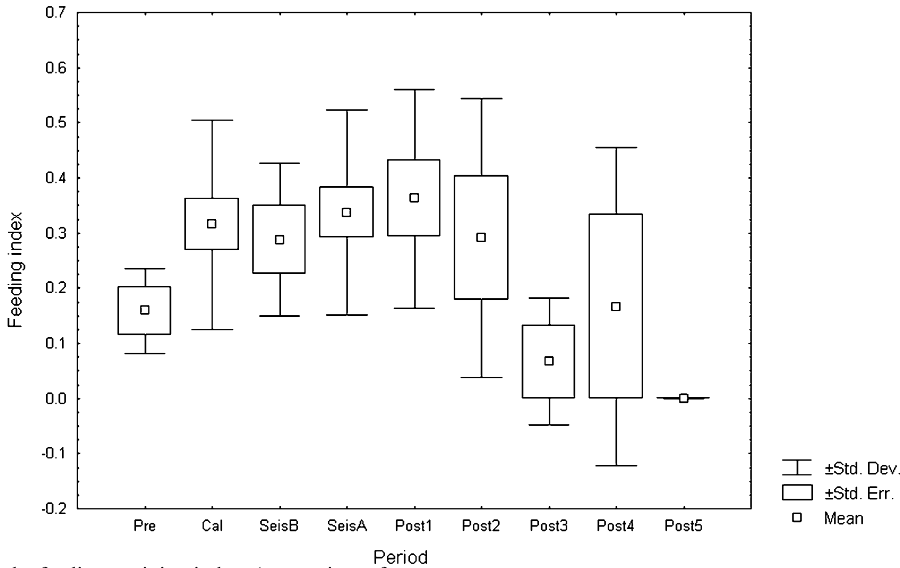

Fig. 3 Gray whale feeding activity index (proportion of gray whale groups definitely associated with mud feeding plumes relative to all observed gray whale groups) recorded on-transect in the Piltun survey area averaged over different periods of the Odoptu seismic survey in 2001. Period codes are as follows: *Pre* – "pre-seismic" period, July 19–Aug 2 (morning); *Cal* – "calibration," Aug 2 (afternoon)–Aug 16; *SeisA* – "seismic survey phase Am," Aug. 17–20 (relatively lower sound levels nearshore); *SeisB* – "seismic survey phase B," Aug. 21–Sept 9 (relatively higher sound levels nearshore); *Post1* – "post-seismic phase 1," Sept. 9–19; *Post2* – "post-seismic phase 2," Sept. 20–30; *Post3* – "post-seismic phase 3," Oct 1–10; *Post4* – "post-seismic phase 4," Oct 11–20; *Post5* – "post-seismic phase 5," Oct 21–Nov 19. Sightings within the blind strip beneath the aircraft (<200 m from the transect on each side of the aircraft at the survey altitude of 300 m ASL) are not included

Figure 3 compares the mean feeding activity index observed before, during and after the seismic survey. The changes in the range of feeding activity indices increased significantly (two-tailed t test; p=0.007) from pre-seismic period (19 July–2 August morning) to calibration period (2 August afternoon–16 August), and remained unchanged from the calibration period through the seismic period, indicating that gray whales continued to be engaged in feeding activity at approximately a constant rate from early August throughout the duration of the seismic survey (17 August–9 September). Feeding activity indices show more variability after seismic survey stopped. Feeding activity did not significantly change for about 3 weeks after the end of seismic survey (periods Post1 and Post2: 9–30 September 2001) but significantly decreased (*vs* seismic survey period) during period Post3 (1–10 October 2001; two-tailed t test; p= 0.003) and ceased during period Post5 (21 October–19 November 2001).

The only environmental variables selected by stepwise multiple regression were transect line and swell height. Total estimated sound level during the previous 3-day period (p=0.183) or previous 3-h period (p=0.54) did not explain a significant amount of residual variation when added to the environmental variable model. The final model of average proportion of western gray whale groups observed with mud plumes in 2001 is given in Eq. 3.

$$\ln\left(\frac{E[\pi]}{1-E[\pi]}\right) = -0.0929 + 2.0088(line = 1) - 0.3546(swell\_hgt) \tag{3}$$

Standard errors, 95% confidence intervals, and significance of each term in the final model are presented in Table 3. Temporal autocorrelations in residuals of the final model that were close in time were around zero (Moran's I=0.045, 95% CI=−0.41 to 0.50). Table 3 and Fig. 4 show the probability that a whale group was associated with mud plume(s) as a function of swell height for Transects 1 and 2. Figure 4 suggests that swell height negatively affects observed whale feeding activity. The negative relationship may be partly attributable to the decreasing visibility of mud plumes under increasing swell height.

Table 3 Coefficients, standard errors, test-statistics, p values, and odds ratio estimates for variables in the final logistic regression model for the gray whale feeding activity analysis

Parameter	DF	Odds ratio estimate	Standard error	χ^2	p value
Intercept	1	−0.0929	0.4901	0.036	0.8497
line=1	1	2.0088	0.4401	20.83	<0.0001
swell_height	1	−0.3546	0.1425	6.19	0.0128

Discussion

The difficulty in studying the effect of noise on foraging-related activity in most baleen whales is exemplified by the dearth of literature on this subject (but see Malme et al. 1986; Miller et al. 1999; Richardson et al. 1995; Richardson 1999). The proximity of western gray whales in the Piltun feeding area to the summer 2001 seismic survey necessitated monitoring the possible effects of seismic survey noise on their foraging activities. Because gray whales are the only baleen whales that are predominantly bottom-feeders, they often create highly visible mud plumes at the surface as they forage on benthic prey. These mud plumes were used to identify gray whales feeding on benthos rather than whales engaged in feeding on non-benthic organisms, traveling, resting, or other activities.

The association of visible mud plumes with successful bottom feeding that results in high quality and quantity of food intake is only a hypothesis that is based upon direct underwater observations of feeding whales, studies on and near feeding troughs, stomach content of harvested whales and linked whale/prey distribution data. An unknown proportion of the dives that produced mud plumes may have been unsuccessful attempts to feed. Therefore, the utility of mud plumes as proxies of successful bottom feeding remains unknown. Available data indicate that both eastern gray whales (Thomson 1983; Bass 2000; Dunham and Duffus 2001, 2002; Meier 2003; Moore et al. 2003; Patterson 2004) and western gray whales (Fadeev 2003, 2004, 2005) consistently feed in areas with high biomass of potential prey and tend to avoid areas with low prey biomass.

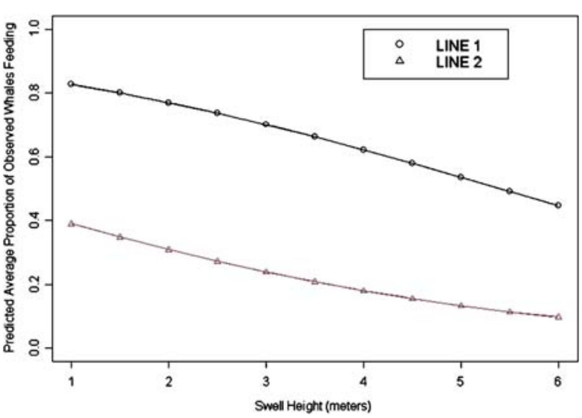

Fig. 4 Predicted average proportions of gray whales with mud plumes as a function of swell height (m) on transect lines 1 and 2

There are other factors that confound interpretation of mud plume sighting data as a direct measure of feeding activity. The sightability of mud plumes was potentially affected by a variety of factors, some of which were analyzed (mainly weather conditions), while others (e.g., bottom sediment type, water turbidity, etc.) were not considered due to lack of site-specific data.

This study is the first systematic study of possible effects of a seismic survey on the feeding of western gray whales. Few studies addressing potential effects of seismic survey noise on the feeding of gray whales have emerged over the last 20 years. Eastern gray whales in the Chukchi Sea did not appear to respond to distant (>36 km) seismic noise (Ljungblad et al. 1982). In one study in the Bering Sea, 10% of eastern gray whales stopped feeding at received seismic sound levels >163 dB re 1 μPa, while other whales continued feeding at 177 dB re 1 μPa (Malme et al. 1986). In that study, whales that stopped feeding and moved away from strong noise levels resumed feeding within 1 h after seismic noise ended. During the Odoptu 3-D seismic survey no overt reactions to seismic sounds similar to those reported by Malme et al. (1986) were noted and no displacement from the general feeding area was observed (Yazvenko et al. 2002, 2007; Würsig et al. 2002; Gailey et al. 2007).

We assessed the effects of seismic surveys on the percentage of whale groups engaged in foraging activity in the entire Piltun feeding area, as well as within individual blocks varying in proximity to the seismic operations. We did not detect significant (p=0.183 for sound measured during the previous 3-day period; p=0.54 for sound measured during the previous 3-h period) changes in the proportion of groups of whales with mud plumes during the Odoptu 3-D seismic survey. In a companion paper (Yazvenko et al. 2007), statistical models suggest that during the 3-D seismic survey in 2001, about 5–10 whales (corrected for availability) may have moved from the portion of the Piltun feeding area immediately west of the Odoptu block southward to the portion of the Piltun feeding area nearer the mouth of Piltun Bay.

The analysis was structured to investigate possible effects on an hourly, daily and weekly temporal scales. Possible short-term (h) and mid-term (several days) changes in whale feeding activity index were examined using a set of seismic survey-related variables (Table 2). None of the hour-scale or day-scale seismic survey-related variables that were tested were found to have effect on feeding activity of whales at $\alpha=0.05$. However, the power of the analyses presented here may be limited, judging by the high variability in the feeding activity index data (Fig. 3).

A companion study of the distribution of western gray whales found that hour-scale seismic survey-related variables were not correlated with the distribution of whales (Yazvenko et al. 2007). Only one seismic survey-related variable, sound energy accumulated over the preceding 3 days, was significantly correlated with the distribution of gray whales, indicating that the noise was having an effect on the distribution of whales on the scale of days but not of hours.

Another companion study investigated the effect of the 2001 seismic survey on onshore western gray whale counts. None of the seismic survey-related variables examined in this analysis explained a significant amount ($p<0.05$) of residual variation in whale counts. *P* values ranged from 0.24 to 0.95 (Würsig et al. 2002; Gailey et al. 2007).

In the study of gray whale behavior (Gailey et al. 2007) changes in 5 out of 11 monitored behavioral traits were found to be significantly correlated with seismic survey variables, which may indicate that whales traveled more during periods of higher seismic sound energy exposure.

The mitigation strategy employed during the 2001 Odoptu 3-D seismic survey (Johnson et al. 2007) was based on the existing literature on gray whales and other cetaceans, and calibrations were made to determine the buffer distance needed to reduce exposure levels below those known to cause cessation of feeding and avoidance responses. Mitigation minimized the number of gray whales that were exposed to seismic sound levels above 163 $\mathrm{dB_{rms}}$ re 1 μPa (Johnson et al. 2007). Throughout the 2001 feeding season, gray whales continued to occupy the main feeding area along the northeast Sakhalin Island coast adjacent to Piltun Bay, and no data indicated displacement outside the Piltun feeding area (Yazvenko et al. 2002, 2007). This is consistent with other studies that suggest gray whales have been using the Piltun location as the primary feeding area every year since 1984 for which distribution data on gray whales were collected (Blokhin et al. 1985, 2002, 2003, 2004; Berzin et al. 1988, 1990, 1991; Blokhin 1996; Würsig et al. 1999; Weller et al. 2000, 2001, 2002, 2004; Sobolevsky 2000, 2001; Yazvenko et al. 2002; Vladimirov et al. 2005, 2006). This is also consistent with the report that there was no indication that western gray whales exposed to seismic survey noise in 1997 were displaced away from the Piltun feeding area (Würsig et al. 1999).

Studies of western gray whales conducted in 2002–2005 indicate no apparent population-level, or biologically significant (NRC 2005) effects of the 2001 seismic survey either on the number of gray whales present in subsequent years (Blokhin et al. 2003, 2004; Vladimirov et al. 2005, Meier et al. 2007), body condition (Weller et al. 2002, 2004; Yakovlev and Tyurneva 2003, 2004, 2005), or reproductive success (Weller et al. 2002, 2004; Yakovlev and Tyurneva 2003, 2004, 2005). Comparisons among years for all monitored behavioral parameters revealed no statistically significant differences between the results of 2001 and 2002–2003, years in which no industrial activity took place near the Piltun feeding area (Würsig et al. 2002, 2003, 2004). Recent estimates of the size of the non-calf component of the western gray whale population indicate 122 individuals in the population in 2005 *vs* ca. 100 in 2001 (Weller et al. 2002; Cooke et al. 2006). In spite of this encouraging evidence, the population remains severely endangered, and its future is highly uncertain.

Conclusions

Available data do not show statistically significant effects of the Odoptu 3-D seismic survey on the bottom feeding activity of western gray whales in the vicinity of Piltun Bay:

1. The overall feeding activity index (proportion of whale groups with visible mud plumes per all

observed groups) of western gray whales in the vicinity of the Piltun Bay in 2001 did not show statistically significant ($\alpha=0.05$) correlation with the Odoptu 3-D seismic survey (Fig. 3). One of the goals of the mitigation strategy was to ensure that gray whales did not significantly change their feeding activity during the seismic survey. Available data suggest that the whales continued to be engaged in bottom feeding activity during the seismic period at levels that were similar to or higher than those in the pre- and post-seismic survey period.

2. The only environmental variables selected by the stepwise multiple regression that explained a statistically significant proportion of variation in the whale feeding index data were transect line (proxy for depth) and swell height (proxy for overall sea condition). Seismic survey-related variables, viz., total estimated sound level during the previous 3-day period or previous 3-h period, did not explain a significant amount of residual variation when added to the environmental variable model. The p values for these two variables were 0.183 and 0.54, respectively.

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